

# Prompt optical observations of GRBs with "Pi of the Sky" system

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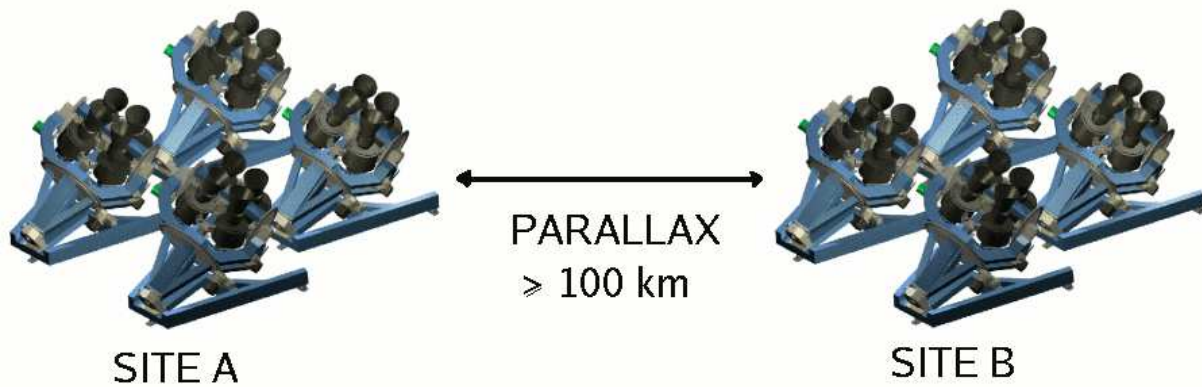
**Abstract.** The "Pi of the Sky" prototype apparatus observed prompt optical emission from extremely bright GRB080319B since the very beginning of the gamma emission. The burst occurred at redshift  $z=0.937$  and set the record of optical luminosity reaching 5.3 mag. The position of the burst was observed before, during and after the explosion by several telescopes and unprecedented coverage of optical light curve has been achieved. The combination of these unique optical data with simultaneous gamma-ray observations provides a powerful diagnostic tool for the physics of the GRB explosion within seconds of its start. The "Pi of the Sky" prototype, working since 2004 in Las Campanas Observatory in Chile, consists of 2 cameras observing same  $20^\circ \times 20^\circ$  fields in the sky with time resolution of 10 seconds. The prototype reacts to GCN alerts, but it has also its own algorithm for identification of optical flashes. The final system covering field of view of Swift or Fermi satellite will consist of 2 arrays of 16 cameras installed in a distance of about 100 km. The system is currently under construction. It will be a powerful tool for early optical observations of GRBs, allowing for optical observation of GRBs before, during and after the gamma emission. With the on-line data analysis in real time, it will identify short optical flashes autonomously and will be able to distribute this information among the community. In this contribution the general idea of the final version of the experiment and the most interesting results from the prototype are presented.

**Keywords:** GRB, prompt optical emission, optical flashes, robotic telescopes, GRB080319B, naked-eye burst

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## INTRODUCTION

Observation of prompt optical emission accompanying gamma-ray bursts (GRBs) can give deeper insight into mechanisms of the radiation and the central engines powering these extreme explosions. Despite impressive advances over the roughly three decades since GRBs were discovered [1], catching prompt optical signal still remains a matter of fortune. Very large progress has been achieved since the first optical counterparts of GRBs were observed in 1997 thanks to Beppo-SAX satellite. In that time faint optical counterparts were observed many hours or even days after the gamma-ray explosion. However, early observation of GRB990123 by the ROTSE robotic telescope [2] has proven that prompt optical signal can also be very significant. Hunting for prompt optical emission from GRBs triggered dynamic development of robotic telescopes. After obtaining alert from the Gamma-Ray Burst Coordinates Network (GCN) [3], they can reach the position of the burst within several dozen of seconds and in many cases even faster. Large progress in the area has been achieved after Swift satellite [4] was launched in November 2004. The Burst Alert Telescope (BAT) detector [5] onboard Swift satellite can immediately provide position of the bursts with precision of 3 arcmin. The UVOT telescope onboard Swift can perform follow-up optical observations very quickly. However, in both cases of the UVOT and ground based robotic telescopes the time delay between the burst and first optical observations is inevitable. Typically UVOT starts observations 60 seconds after the bursts, reaction time is sometimes shorter in case of robotic telescopes depending on the angular distance from the bursts. In spite of the fact that an enormous progress in fast optical follow-ups has been achieved, the very first moment of the bursts is still rather a "dark era" as far as optical observations are concerned. There were only few events for which the optical signal was observed



**FIGURE 1.** Configuration of final system, able to cover whole Swift's field of view.

during the gamma-ray emission. The most famous one was GRB990123 observed by ROTSE [2], the other one was the GRB041219 observed by RAPTOR [6]. These two events were observed very early quite serendipitously, the first one occurred in the field of view (FOV) of the ROTSE wide field camera, the later was triggered by the precursor and the alert was sent to GCN network before the main burst has started. Apparently a new approach is needed to illuminate the "dark era" of prompt optical observations. The solution was postulated by late prof. B. Paczynski, who proposed to use wide field robotic telescopes for observations of early optical emission from GRBs [7]. This idea was beautifully confirmed by recent observation of the naked-eye GRB080319B performed by the prototype of the "Pi of the Sky" system. The final system, which is currently under construction, will be much more powerful tool for early optical observations of GRBs.

## "PI OF THE SKY" SYSTEM

### Final System Design

The idea of continuous observations of the very wide field is to be realized by the "Pi of the Sky" system. The system will consist of two farms of 16 cameras (Fig.1), installed in a distance of  $\geq 100$  km. Each camera will cover field of view of  $20^\circ \times 20^\circ$ , which will result in a total sky coverage of  $\sim 2$  steradians. This corresponds to field of view of Swift BAT [5] and Fermi LAT [8] detectors. Every GRB detected by the Swift, in the observing range of the "Pi of the Sky" system, will already be in its field of view. It is expected that  $\sim 1/5$  of all GRBs will occur in the FOV of the system [9]. They will be observed with 10 s time resolution since the very beginning of the burst, without any time delay normally needed to re-point the telescope. Moreover, the area of interest will be observed even before the GRB, allowing to observe or determine the upper limits for brightness of optical precursor. The algorithms will analyze the images in the real time in search for short optical flashes [9]. The two sets of 16 cameras will observe the same part of the sky. The large distance between two sets is needed by the algorithms to use parallax to reject short optical flashes caused by artificial satellites and other near Earth sources.

The price for wide field observations is the limiting magnitude, which is  $12^m$  on single 10 s exposure and reaches  $14\text{--}15^m$  on 20 averaged images. However, predictions for the final system are very promising, the conservative estimation gives  $\sim 2$  GRB events per year to occur in its FOV and bright enough to be detected [9]. The number of positive detections can be even larger, because Fermi satellite was not taken into account in this analysis. Another interesting perspective is a possibility of observing optical counterparts of short GRBs. Recent observations of optical counterparts of short GRBs indicate that they are much dimmer than long ones, but they were never observed in the very first moment of the explosion. The system is currently under construction, it is planned to be installed in 2009 in Europe, probably somewhere in the Mediterranean region.

## Prototype working in Las Campanas Observatory

Design and development of the prototype was the first step towards the final "Pi of the Sky" system. The prototype was installed in Las Campanas Observatory in Chile in June 2004. It consists of two custom designed, low noise cameras [10] installed on a parallactic mount. Each camera has a CCD with  $2000 \times 2000$  pixels of  $15 \times 15 \mu m^2$ . They are equipped with CANON EF  $f = 85$  mm,  $f/d = 1.2$  photo lenses, giving pixel scale of 36 arcsec/pixel and covering  $20^\circ \times 20^\circ$  field of view. Currently the system observes sky in white light and only UV/IR-cut filter (transparent in 390-690 nm) is used to suppress the background. The cameras continuously collect 10 s images with 2 s breaks for readout. The values of limiting magnitude are the same as expected for the final system (see above). The cameras work in coincidence and observe the same field in the sky. The system works fully autonomously, it sends SMS and e-mail to an operator in Warsaw, in case of GRB alert or any problems. For most of the time the telescope follows center of the Swift satellite's FOV. The coordinates of Swift's pointing are obtained from the GCN network. In case Swift's FOV cannot be observed, an alternative target like Integral or interesting object from list of blazars or AGNs [11] is chosen. Twice a night whole sky scan is performed. The on-line algorithm analyzes subsequent images in real time in search for short optical flashes of cosmic origin.

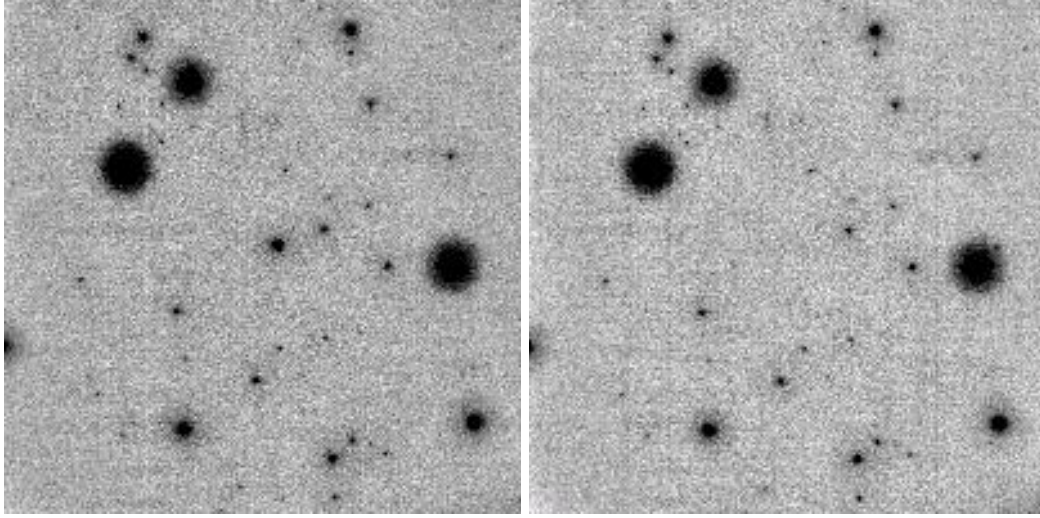
## Data Analysis

The data analysis in the "Pi of the Sky" project consists of on-line and off-line parts. The on-line algorithm analyzes images in real time in order to find short optical flashes on the time scale of seconds or more. The algorithm was based on idea of multilevel triggering system typical for high-energy physics experiments. Subsequent images are compared in order to find objects which appear in the new image and were absent on series of previous images. After first two steps of the algorithm all pixels suspected of being new objects in the sky are identified. Then several cuts are applied in order to reject background candidates. The most important cuts are :

- **Coincidence** - this cut requires new object to be detected in both cameras at the same position in the sky. It rejects mostly cosmic rays hitting one of CCD chips.
- **SatCatalog** - optical flashes due to artificial satellites are rejected by using catalog of orbital elements retrieved daily from the Internet.
- **StarCatalog** - rejects fluctuations of edges of bright stars according to star catalog
- **Track** - fits tracks to objects from many subsequent images (typically 200) in order to reject moving objects (i.e. satellites or planes) which could not be rejected by previous **SatCatalog** criteria
- **Shape** - Point Spread Function (PSF) of the event is tested and elongated objects are rejected.

The above cuts allow to suppress background efficiently without losing too much signal. The algorithm was tested on real data. The efficiency of optical flashes identification strongly depends on the weather conditions, reaching 80% for flashes brighter than  $9^m$  during clear, moonless nights. The details of the algorithm can be found elsewhere [9]. This algorithm automatically identified about 200 short optical flashes of unknown origin. Two events were unambiguously confirmed as flashes of astrophysical origin. The first one was an outburst of flare star CN Leo observed on 2.04.2005 [12]. The greatest success of the algorithm was identification of optical flash related to GRB080319B. Most of the optical transients were not cross identified with any astrophysical events from other experiments. Observations of short optical flashes may be very useful tool for identification of orphaned prompt optical signal from GRBs. Current measurements from the prototype limit number of bright optical flashes related to GRB-like events to  $\leq 4$  /day/ $4\pi$  [9].

The raw data is reduced by custom designed reduction pipeline ([9],[13]) and measurements of star brightnesses are catalogued in a database. The database, consisting of millions of stars brightness measurements, is analyzed by the off-line algorithms ([9],[14]) in order to find new objects which appeared in the sky or brightening of existing objects in time scales ranging from minutes to days. Several nova stars were recently discovered by this kind of analysis [15].



**FIGURE 2.** Optical counterpart of the GRB 080319B, left image with very bright optical signal in the center (taken at 06:14:03 UT) and right image without optical transient (taken 10 minutes after the burst)

## PROMPT OPTICAL OBSERVATIONS OF GRBS

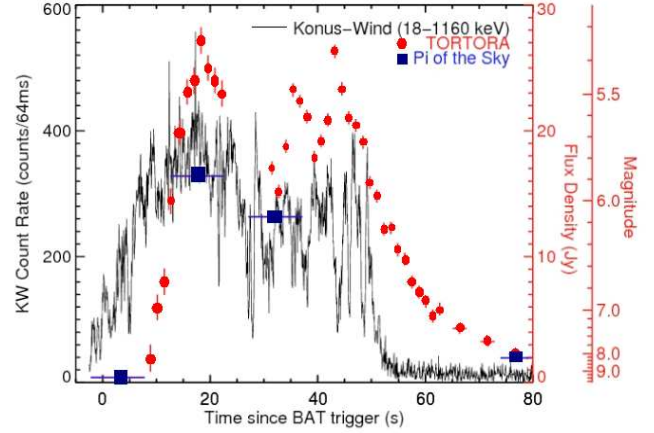
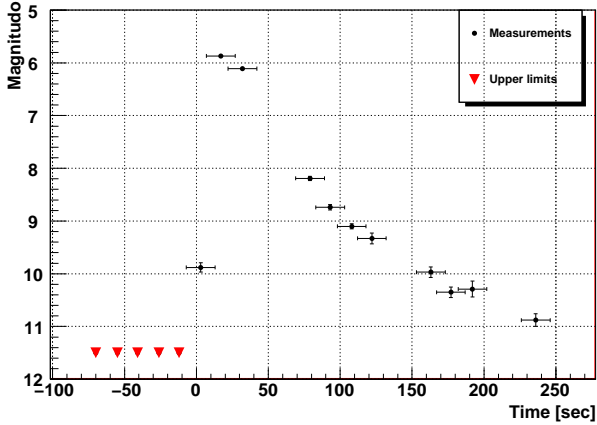
### Observation of the GRB080319B

On March 19, 2008, at 06:12:49 Universal Time the BAT detector onboard the Swift satellite [5] was triggered by an intense pulse of gamma rays from GRB 080319B [16]. The BAT localization distributed over the GCN at 06:13:06 was received by the "Pi of the Sky" system, while the follow-up of previous alert (GRB 080319A) was still in progress. The angular distance of GRB 080319B from position of GRB 080319A was  $\alpha \approx 11.76^\circ$ , which was small enough to catch GRB 080319B in the FOV of the telescope. The "Pi of the Sky" telescope has observed the area of interest for 23 min 33 sec before the burst. The first exposure on which optical signal from GRB 080319B was detected has started at 06:12:47 Universal Time, two seconds before the outburst was detected by the BAT. Very bright optical flash has been automatically detected by the on-line algorithm searching for short optical transients. The optical signal was bright enough to be observed by the "Pi of the Sky" telescope for next 4 minutes (Fig. 2), after that time it faded below the limiting magnitude of the system [17]. The maximal brightness of the optical transient reached  $5.3^m$  which means that the event which occurred in a distance of almost 7.5 billion years could be visible with a naked-eye. The optical flux was normalized to V filter magnitude of the neighboring stars using the procedure described in [9]. The measurements are listed in Table 1, systematic errors shown in this table are due to normalization of unfiltered observations to V filter brightness. The optical lightcurve is shown in Figure 3. Observation of GRB 080319B confirms strongly that the wide field cameras are the best and probably the only effective way for observations of prompt optical signal. The unprecedented coverage of the optical lightcurve was a key for understanding the physics of the event. The results of multiwavelength analysis of GRB 080319B show that early optical observations can have very significant impact on modeling the phenomena [18]. As it can be seen from Fig. 3 optical signal starts and ends in the same moment as gamma emission. This can prove that optical signal is produced in the same region as gamma rays. On the other hand optical flux is 3-4 orders of magnitude larger than gamma ray spectrum extrapolated to optical region, suggesting different production mechanisms. Even observation of the one single GRB can have large influence on the existing models of these mysterious events [18]. This exhibits how much the GRB understanding suffers from lack of the early optical data.

### Early limits on other GRBs

The "Pi of the Sky" system is working since June 2004. Since then until now (2008.12.18) about 360 GRBs with known position were observed by the satellites, most of them occurred outside the range of the telescope and could not

"Pi of the Sky" observation of GRB 080319B



**FIGURE 3.** Optical lightcurve of GRB 080319B measured by the "Pi of the Sky" prototype (left plot, points are centered in central time of the exposure and 10 s error bar corresponds to exposure time) and early optical measurements with  $\gamma$ -ray lightcurve superimposed (right plot from [19])

**TABLE 1.** Brightness of optical counterpart of GRB 080319B on 10 s images

| Start Time (UT) | V        | $\delta_{stat}$ V | $\delta_{sys}$ V | flux [Jy] | $\delta_{stat}$ f [Jy] | $\delta_{sys}$ f [Jy] |
|-----------------|----------|-------------------|------------------|-----------|------------------------|-----------------------|
| $\leq 06:12:32$ | $> 11.5$ | -                 | -                | $< 0.095$ | -                      | -                     |
| 06:12:47        | 9.88     | 0.09              | 0.14             | 0.42      | 0.04                   | 0.06                  |
| 06:13:01        | 5.87     | 0.03              | 0.27             | 17.0      | 0.5                    | 4.24                  |
| 06:13:16        | 6.11     | 0.03              | 0.27             | 13.6      | 0.4                    | 3.38                  |
| 06:14:03        | 8.19     | 0.04              | 0.17             | 2.00      | 0.07                   | 0.31                  |
| 06:14:17        | 8.74     | 0.05              | 0.16             | 1.20      | 0.06                   | 0.18                  |
| 06:14:32        | 9.10     | 0.05              | 0.15             | 0.87      | 0.04                   | 0.12                  |
| 06:14:46        | 9.33     | 0.10              | 0.14             | 0.70      | 0.06                   | 0.09                  |
| 06:15:27        | 9.97     | 0.10              | 0.14             | 0.39      | 0.03                   | 0.05                  |
| 06:15:41        | 10.35    | 0.10              | 0.15             | 0.27      | 0.03                   | 0.04                  |
| 06:15:56        | 10.29    | 0.15              | 0.15             | 0.29      | 0.04                   | 0.04                  |
| 06:16:40        | 10.88    | 0.12              | 0.15             | 0.17      | 0.02                   | 0.02                  |

be observed. In three cases (except GRB 080319B) the burst occurred in the FOV of the telescope and upper limits for prompt optical emission have been determined (Tab. 2). In some other cases GRB position was reached in less than two minutes, such limits are also listed in the Table 2. In none of these cases optical counterpart was observed.

## SUMMARY

The prototype of the "Pi of the Sky" system working in Las Campanas Observatory in Chile has observed prompt optical emission from GRB 080319B. Unprecedented coverage of the optical lightcurve allowed for precise analysis of this event. It turns out that even single, well measured burst can challenge the mainstream models of GRBs. This observation have proven that the best way for observing early optical signal from GRBs is to use wide field cameras. The final "Pi of the Sky" system able to cover whole FOV of the Swift satellite is currently under construction. It is expected that  $\sim 1/5$  of all Swift's GRBs will occur in the FOV of the system and at least 2 long GRBs per year will be bright enough to be observed by the system. Another great opportunity of such farm of wide field cameras is a possibility of observing short GRBs in the very first moment of the explosion.

**TABLE 2.** Upper limits on brightness of prompt emission for GRBs which occurred in FOV of the "Pi of the Sky" system or have been observed less then 2 minutes after the GRB

| GRB            | Reaction Time [seconds] | Before            | During            | After             | During or After [Jy] |
|----------------|-------------------------|-------------------|-------------------|-------------------|----------------------|
| <b>040825A</b> | <0                      | 10.0 <sup>m</sup> | 12.0 <sup>m</sup> | 9.5 <sup>m</sup>  | 0.06                 |
| <b>050412</b>  | <0                      | 11.5 <sup>m</sup> | 11.0 <sup>m</sup> | 11.5 <sup>m</sup> | 0.15                 |
| <b>070521</b>  | <0                      | 12.2 <sup>m</sup> | 12.6 <sup>m</sup> | 12.5 <sup>m</sup> | 0.035                |
| 080916A        | 66                      | -                 | -                 | 11.3              | 0.11                 |
| 080805         | 83                      | -                 | -                 | 12.2              | 0.05                 |
| 080804         | 101                     | -                 | -                 | 12.0              | 0.06                 |
| 080409         | 96                      | -                 | -                 | 12.0              | 0.06                 |
| 080310         | 99                      | -                 | -                 | 12.4              | 0.04                 |
| 081007         | 71                      | -                 | -                 | 12.1              | 0.05                 |
| 070913         | 110                     | -                 | -                 | 12.6              | 0.034                |
| 060719         | 65                      | -                 | -                 | 12.8              | 0.03                 |
| 050607         | 60                      | -                 | -                 | 12.5              | 0.04                 |
| 050522         | 75                      | -                 | -                 | 11.0              | 0.15                 |

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